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Dynamical evolution of 1036 Ganymed, the largest near-Earth asteroid

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Abstract. We have studied numerically the dynamical evolution of 1036 Ganymed, the largest near-Earth asteroid, by integrating the orbits of tens of "clone" particles with similar initial conditions. Typically, the orbit initially undergoes large, coupled oscillations of the eccentricity and inclination; then, Mars encounters random–walk the semimajor axis until it reaches a strong Jovian resonance; and eventually, resonant effects pump up the eccentricity until the orbit becomes Sun–grazing or hyperbolic (after encountering Jupiter). The median dynamical lifetime is of about 10 Myr. Most orbits become Earth–crossing within 10 Myr of evolution. The origin of Ganymed and a few other sizable Mars–crossing asteroids with similar orbital elements is an open problem, since the main–belt asteroid population in the neighbouring lower–eccentricity portion of the phase space is quite sparse. Although Ganymed's reflectance spectrum has some similarity to those of the ordinary chondrites, the Earth delivery efficiency from bodies with this type of orbits is low, because they are short–lived after they become Earth–crossing.

Key words: celestial mechanics, stellar dynamics – meteors, meteoroids – minor planets, asteroids

1. Introduction

The dynamics of near–Earth asteroids (NEAs) is probably the most difficult problem in Celestial Mechanics, due to the complex interplay of close encounters, secular perturbations and/or resonances, and mean motion resonances, resulting into a variety of instabilities, protection mechanisms and evolutionary effects. Although this was already apparent from work carried out in the 80's (Milani et al. 1989), only in the current decade computers have become fast enough to allow for numerical experiments covering time spans (1–100 Myr) comparable to the dynamical lifetimes of these objects and providing insights into the main evolutionary *routes* (Farinella et al. 1994; Froeschlé et al. 1995; Valsecchi et al. 1995; Michel et al. 1996a,b,c, 1998; Michel 1997; Gladman et al. 1997; Migliorini et al. 1998).

The interest of these studies is due to the proximity of these small bodies to the Earth, which results in a significant long–term impact hazard for our planet, but also in the accessibility by dedicated space missions (such as the ongoing NEAR mission to 433 Eros). Of course, the largest NEAs are among the most interesting from both these points of view. Moreover, for diameters exceeding ≈ 5 km the observed sample of NEAs is probably almost complete, and therefore in order to draw meaningful conclusions on the origin and dynamical evolution of these bodies one does not need to get involved with the complex issue of observational selection effects. These motivations have recently led Migliorini et al. (1998) to study in a statistical way the dynamical evolution of a large sample of Mars–crossing asteroids larger than 5 km, showing that they provide a plausible source for the observed Earth–crossing population at these sizes.

In this paper, following our earlier work on 433 Eros (Michel et al. 1996b,c, 1998), we adopt a different strategy: instead of studying statistically a sample of several hundred different objects, we analyze the likely dynamical history of a single big object, 1036 Ganymed. Of course, due to the strongly chaotic character of all the NEA orbits (see e.g. Whipple 1995), our conclusions will again be statistical and will be based on a sample of many different *clone* integrations, starting from a set of nearby initial conditions. As a consequence, our conclusions will be relevant not for the entire Mars–crossing and/or near–Earth populations, but for its subset with current orbits similar to those of the selected object (1036 Ganymed), for which we shall estimate the dynamical lifetimes and assess the most important evolutionary mechanisms.

1036 Ganymed has a mean diameter in the range between 30 and 40 km, and as such is the largest NEA. The second largest NEA is 433 Eros with a mean diameter ≈ 20 km, then 3552 Don Quixote (≈ 12 km), followed by about 18 NEAs with diameter in the range between 5 and 10 km. Note, however, that this depends in part on the arbitrary criterion of defining NEAs as those objects with perihelion distance $q < 1.3$ AU — as we shall see (Sect. 4), larger Mars–crossing asteroids do exist, although with somewhat higher values of q. Anyway, Ganymed is certainly one of the largest members of the planet–crossing asteroid population, and as such its origin is an interesting question. For instance, Zappalà et al. (1997) have recently speculated that it might be a sizable former member of the Maria asteroid family,

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Table 1. Starting osculating orbital elements of 1036 Ganymed.

Epoch $10/10/95$ J.D. Invariable Plane Equinox 2000.0
The elements were taken from the Ephemerides of Minor Planets 1995.

a (AU)	e	i	Ω	ω	M (mean anomaly)
2.6594698	0.5381035	$27^\circ.15922$	$215^\circ.20601$	$128^\circ.97002$	$122^\circ.37330$

which is close to the outer edge of the 3:1 Kirkwood gap in the main belt and whose members have S–type visible reflectance spectra quite similar to those of Ganymed (and Eros). In this scenario, Ganymed would be a large fragment from a catastrophic break–up event, perhaps similar to the Koronis family member 243 Ida encountered in 1994 by the Galileo spacecraft (Davis et al. 1996). Following its ejection in the family–forming event, it would have been inserted into the resonance, and as a consequence would have had its orbital eccentricity pumped up to planet–crossing values. In this context, it is also interesting to note that Ganymed is so big that the non–gravitational Yarkovsky perturbation, which has been recently shown to cause a significant drift in the semimajor axis of km–sized main–belt asteroids (Farinella & Vokrouhlický 1999), cannot have affected its orbit much.

Ganymed's current orbit (see Table 1) is very different from that of Eros. Its semimajor axis $a = 2.66$ AU places it fairly close to some powerful mean motion resonances with Jupiter (3:1 at $a \approx 2.501$ AU, 8:3 at $a \approx 2.705$ AU, 5:2 at $a \approx 2.824$ AU), and its fairly high eccentricity ($e = 0.538$) leads it to reach a heliocentric distance of 1.23 AU at perihelion. The inclination ($i = 27^\circ.2$) is also relatively large, higher than the values corresponding to the ν_6 secular resonance, by far the strongest secular resonance, located at $i \approx 18$–19° in that region of the phase space (see e.g. Fig. 7 in Knežević et al. 1991). Migliorini et al. (1998) have grouped this kind of Mars–crossing orbits in a class labelled MB2, and suggested that they are probably genetically related to the main–belt objects with similar values of a and i (but a lower eccentricity). They also noted that these MB2 bodies, accounting for only $\approx 5\%$ of the total population of known Mars–crossers but for over 40% of those larger than 5 km (an indication of a strong observational selection effect against their discovery), cannot contribute much to the Earth–crossing population, because when they reach an Earth–crossing state their semimajor axis typically remains so high that Jovian resonances or encounters remove them fairly quickly (sending them to hit the Sun or into hyperbolic orbits). According to the Migliorini et al. integrations, their typical dynamical half–life is about 40 Myr, but they are very unlikely to reach an "evolved" dynamical state with $a < 2$ AU (Migliorini et al. 1998; Michel et al. 1999).

As for the physical properties of Ganymed, they are quite typical for an S–type asteroid. We refer to McFadden et al. (1989) and Lupishko & Di Martino (1998) for a tabulation and a detailed discussion of the available data for the near–Earth population in general and Ganymed in particular, and to Zappalà et al. (1997) for an analysis of recent spectral observations. We shall discuss in Sect. 4 some implications of Ganymed's spectral properties on the issues of meteorite parent bodies and delivery.

The remainder of this paper is organized as follows. In Sect. 2 we describe our main set of numerical integrations of Ganymed clones, illustrate some examples in detail and analyze the most important dynamical mechanisms which are at work for this type of orbits. In Sect. 3 we summarize the results obtained with two more sets of clones, integrated with a different algorithm, faster but less accurate during close encounters, and discuss the corresponding statistics. The implications of our results and some open problems are discussed in Sect. 4.

2. Bulirsch–Stoer numerical integrations and results

Our main set of numerical integrations were performed using a Bulirsch–Stoer variable step–size algoritm (Stoer & Bulirsch 1980), optimized for dealing accurately with planetary close encounters; with this kind of algorithm, the time step is reduced automatically during the encounters, in a way which is not determined *a priori* but depends on the geometry and speed of the encounters. Our code is also suitable to detect collisions and study the statistics of closest approach distances (for more details, see Michel et al. 1996c). The dynamical model included all the planets except Pluto. The integration time spanned at least 10 Myr in the future (more in some interesting cases).

Like all planet–crossing orbits, Ganymed's orbit is strongly chaotic (i.e. sensitive to the chosen initial conditions, physical model of the Solar System, integration algorithm, computer round–off features...), and therefore the numerical integrations over time spans much longer than the Lyapounov time ($t_L \approx 10^2$ yr, see Whipple 1995) cannot be seen as deterministic predictions of the behaviour of the real orbit, but can provide statistical information on the most common patterns of dynamical evolution and the corresponding time scales. For this purpose, we integrated not only the nominal orbit of Ganymed (i.e., the starting orbital elements given in Table 1), but also a set of "clone orbits", obtained by changing slightly the initial parameters (one at a time). We obtained a first set of 12 clones changing by $\pm$ one unit the last digit of each parameter (semimajor axis a, eccentricity e, inclination i, mean anomaly M, perihelion argument ω and longitude of node Ω). This set of 13 clones (including the nominal orbit) was integrated using one computer, labeled 1. A second set of 8 clones (including again the nominal orbit) was also obtained by small changes in the starting elements, but carrying out the integrations on another computer (labeled 2). Table 2 lists these 21 clones and provides some information on the results of the corresponding 10 Myr integrations.

Table 2. Numerical results on the orbital evolution of Ganymed clones. The clones' labels correspond to the used computer (1 and 2) and the modified orbital element (letters *a*, *e*, *i*, *M*, *o*, *O*). The table lists the resonant mechanisms found to be important (i/j indicates the corresponding mean motion resonances with Jupiter). The end state and time of occurence (Myr) are also given for clones ejected from the Solar System ("Out") or impacting the Sun ("Sun") within 10 Myr.

	Earth–crosser?			Resonances			End State (Myr)		
	Burlisch-	RMSV3		Burlisch-	RMSV3		Burlisch-	RMSV3	
Clone	Stoer	15 *days*	7 *days*	Stoer	15 *days*	7 *days*	Stoer	15 *days*	7 *days*
Gany. 1	Y			8/3 5/2			Out (9.4)		
Gany. 1a+	Y	N	Y	3/1		8/3 3/1	Sun (8.6)		Sun (7.0)
Gany. 1a–	Y	Y	Y		8/3				
Gany. 1e+	Y	Y	N	8/3 5/2	8/3 3/1		Sun (3.9)	Sun (8.9)	
Gany. 1e–	Y	Y	Y	8/3 5/2	5/2 7/3		Sun (5.7)		
Gany. 1i+	N	Y	Y					Out (4.3)	
Gany. 1i–	Y	Y	Y	8/3 5/2	8/3				
Gany. 1M+1	Y	Y	Y	8/3 5/2 2/1	8/3	8/3	Sun (4.5)		
Gany. 1M–1	Y	Y	Y		8/3 7/3	8/3 5/2		Sun (9.7)	Sun (2.7)
Gany. 1o+1	Y	Y	Y		8/3 3/1	8/3 5/2		Sun (7.5)	Sun (9.1)
Gany. 1o–1	Y	Y	Y	3/1 8/3 5/2	7/2 3/1 8/3	8/3 5/2	Out (4.7)	Sun (10.)	
Gany. 1O+1	N	N	Y			8/3			
Gany. 1O–1	N	N	N						
Gany. 2	Y	Y	N	8/3 5/2	3/1 5/2			Sun (6.8)	
Gany. 2a+	Y	Y	N	8/3 3/1	8/3 3/1			Sun (8.6)	
Gany. 2a–	Y	Y	Y	8/3 5/2	8/3 5/2 7/3	3/1		Sun (3.3)	Sun (5.0)
Gany. 2i+	Y	Y	Y	8/3 3/1	8/3 5/2		Sun (6.5)	Sun (7.7)	
Gany. 2e+	Y	Y	Y	3/1 7/2	8/3 5/2			Sun (2.8)	
Gany. 2M+	Y	N	Y	8/3 5/2		8/3 5/2	Sun (5.9)		Sun (4.2)
Gany. 2o+	N	Y	Y		8/3 5/2			Sun (7.5)	
Gany. 2O+	Y	N	Y			8/3 5/2			Sun (2.1)
	17/21	15/20	16/20				9/21	11/20	6/20

Like previous studies of this kind (e.g. Michel et al. 1998), with a limited number of clone integrations, one can never be sure that some rare or unlikely dynamical evolution pattern is not missed. However, our sample of integrations shows a remarkable diversity of dynamical routes and evolutions, resembling that found for the entire MB2 region (Migliorini et al. 1998, Michel et al. 1999). Therefore, we believe that our results are statistically robust, although of course an individual object (such as the real Ganymed) might well behave in an anomalous way.

As shown in Table 2, two Ganymed clones are ejected from the Solar System within the 10 Myr time span. Six other clones hit the Sun within 10 Myr. Continuing the other integrations, we have found that three more clones (1i–, 2 and 2e+) collide with the Sun after 12.4 Myr, 10.8 Myr and 14.9 Myr, respectively. It follows that the median dynamical lifetime of these orbits is close to 10 Myr. It is remarkable that this lifetime is a factor 4 shorter than that of the whole MB2 Mars–crossing sub–population studied by Migliorini et al. (1998), and that the same holds for the time needed for the clones to encounter the Earth. The main reason for this discrepancy is that Ganymed's orbit starts already quite close to some strong Jovian resonances (in particular the 8/3 resonance); as we are going to see, this implies that the random walk phase due to Mars encounters can last only for a relatively short time before a resonant "fast track" is eventually reached.

Actually, Table 2 shows that the majority of the orbits (13 over 21) is strongly affected by some mean motion Jovian resonances (mainly 3/1, 8/3 and 5/2), which typically lead to drastic jumps of the eccentricity over a few Myr (Gladman et al. 1997). 17 clones over 21 become Earth–crossing during their evolution, and remain such for at least 0.3 Myr. This implies that bodies as big as Ganymed (>30 km in diameter) can become the largest Earth–crossing asteroids from time to time (note that today the largest Apollo asteroid is less than 10 km across).

Of course the orbital evolution of the clones on time spans of millions of years is quite diverse, so it is impossible to provide a unique description of the corresponding dynamics. However, a close inspection reveals a number of common features, which we are going to summarize here. First of all, due to the relatively high starting inclinations, all the orbits undergo at the beginning a Kozai–like dynamics, i.e. large coupled oscillations of the eccentricity and inclination, such as to conserve the z–component of the orbital angular momentum (Kozai 1962; Michel & Thomas 1996). Although the minimum perihelion distances get close to $q = 1$ AU, the so–called e–ω protection mechanism prevents close encounters with the Earth, because when ω is close to 0 or $180°$ (i.e., the perihelion passage occurs near a node) the eccentricity is at a minimum of its secular cycle (see Fig. 1).

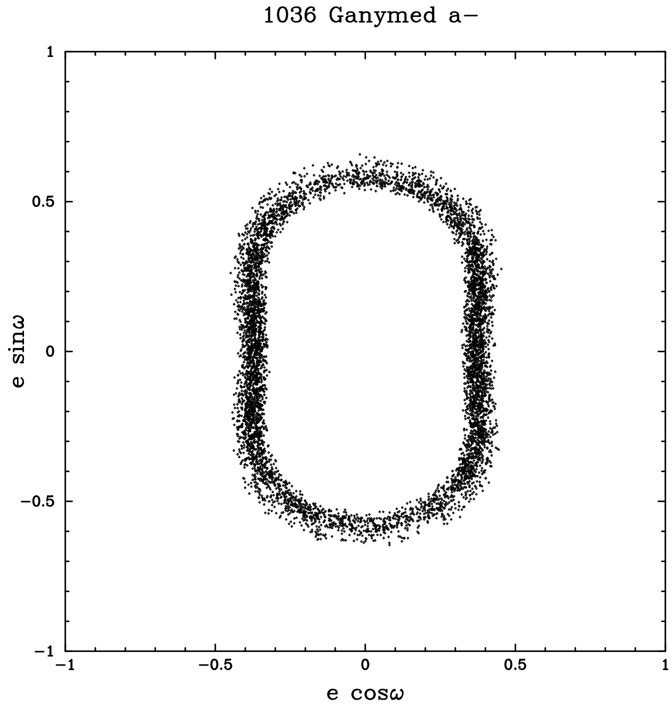

Fig. 1. The evolution in the $e \sin \omega$ vs. $e \cos \omega$ plane of the $a-$ clone. The orbit of this clone is protected by the e–ω mechanism from close Earth encounters over the entire integration time span. Note that when the eccentricity is maximum the perihelion distance gets close to 1 AU, but no close encounter occurs because the body is far away from the ecliptic.

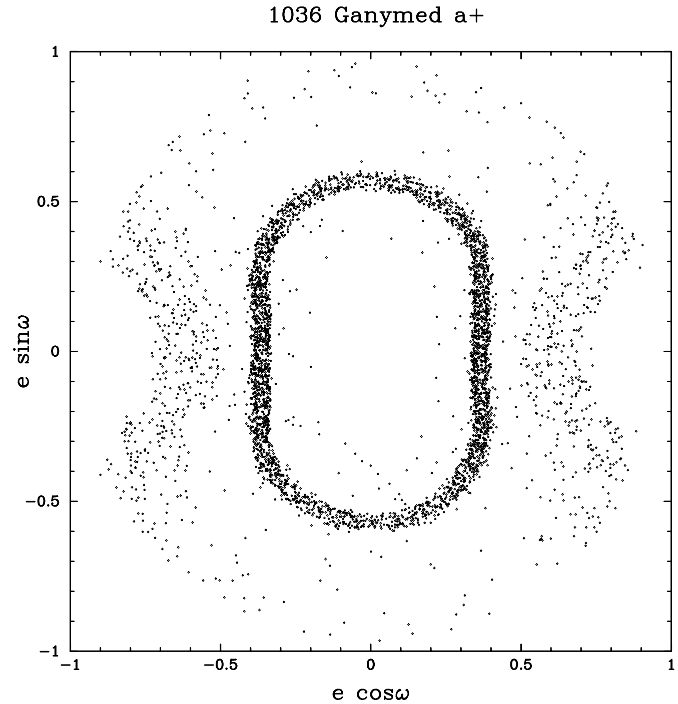

Fig. 2. The same as Fig. 1 but for the $a+$ clone. The e–ω mechanism is effective only for a part of the integration time span, and later on the eccentricity evolves in a chaotic way and reaches much higher values.

The evolutions in which the Kozai–like protection lasts for the entire 10 Myr time span are rather an exception than the rule. For instance, another clone (see Figs. 2, 3, 4) remains in this state for about 6.5 Myr, but in the mean time Mars encounters (against which the e–ω protection mechanism does not work) slowly random–walk the semimajor axis and decrease the minimum perihelion distance until the body suffers an Earth encounter strong enough to throw it into the 3/1 resonance. Afterwards, the eccentricity and inclination rise in a chaotic manner, and after about 2 more Myr the orbit becomes Sun–grazer, in agreement with the findings of Gladman et al. (1997).

Fig. 2 shows for this clone a plot similar to Fig. 1, where the interruption of the Kozai protection pattern is apparent; Fig. 3 shows the corresponding evolution of the a, e, i and $q = a(1-e)$ elements for this orbit; and in Fig. 4, for the 0.2 Myr time span when the body starts to undergo Earth encounters, we have plotted its heliocentric distance at the node–crossings, given by $a(1-e^2)/(1 \pm e \cos \omega)$. This figure shows clearly that initially the node–crossings always occur at distances well above 1 AU (but sometimes lower than Mars's semimajor axis), whereas later on they can happen also close to the Earth's orbit. During the corresponding intervals of time, the close encounters may take place.

The two orbital evolutions discussed so far are quite typical, but more complex variants are also possible. In several cases the 8/3 resonance is reached before the 3/1 one, and quite often Earth or Venus encounters extract the body from one resonance, but then inject it again into the same or another one (including the 5/2 and 2/1 resonances). In all these cases, the post–resonant evolution is qualitatively similar to those found by Gladman et al. (1997) for fictitious particles starting in the resonances, and in particular only in a few cases the clones survive for more than a few Myr after resonance injection. In Fig. 5 we show the behaviour in the a–e plane of six representative clones; note the thick horizontal strips corresponding to the initial e–ω coupling and, in most cases, the subsequent scattering in the vicinity of the semimajor axis values corresponding to the main resonances, leading to very eccentric orbits.

Among the 17 clones which become Earth–crossers (ECs), four of them are transported by close encounters with Mars and are shallow and temporary ECs, when the eccentricity is near the peak of its cycle (see e.g. clone $o+$ in upper right panel of Fig. 5). In these cases the time spent in the Earth–crossing zone ranges from 0.3 to 3 Myr. These orbits never get injected into a resonance and survive over the entire integration time span.

Clones $2a+$ and $2a-$ also become ECs due to close Mars encounters, but then they enter temporarily into some mean motion resonances. Clone $2a+$ falls and stays in the 8/3 resonance between 5.2 and 6.9 Myr after an encounter with the Earth, but then is extracted from it and later on it is put and extracted twice in/from the 3/1 resonance. The eccentricity of this body ranges from 0.2 to 0.9, so during the second complex phase of its evolution it becomes not only an EC, but also a Venus– and a Mercury–crosser. On the other hand, clone $2a-$ is inserted in the 8/3 resonance by a Mars encounter, stays there for 0.3 Myr,

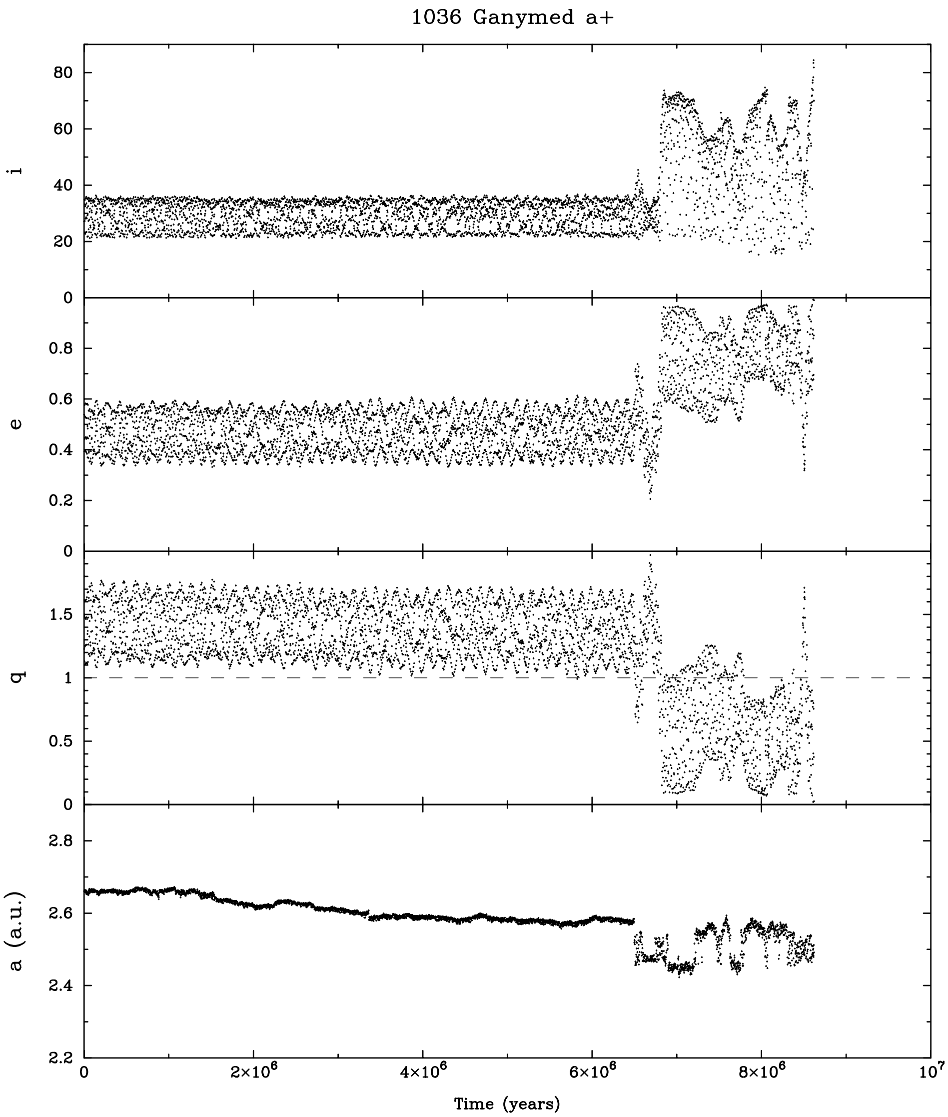

Fig. 3. The evolution of a, q, e and i vs. time for the $a+$ clone until it hits the Sun. In a first phase the orbit behaves in a fairly regular way, although Mars encounters cause a slow random walk in a. After about 6.5 Myr, the 3/1 resonance takes over and the dynamics becomes strongly chaotic.

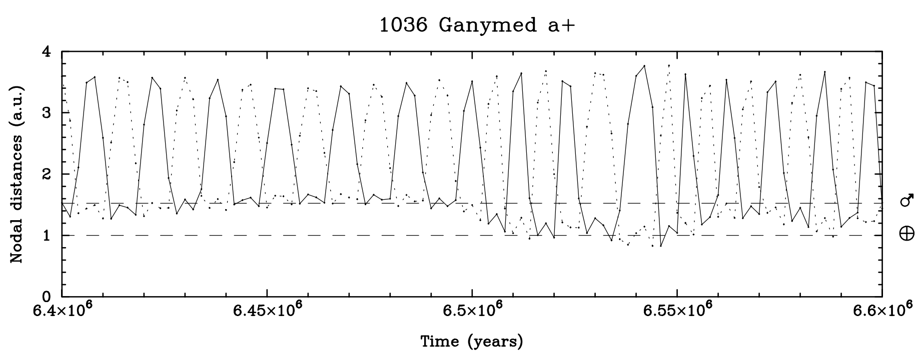

Fig. 4. Heliocentric distances at the node crossings (full line for ascending node, dotted line for descending node) for clone $a+$ in the 0.2 Myr interval when the e–ω protection mechanism is interrupted. The two horizontal dashed lines mark the semimajor axes of Mars and the Earth. The orbit can always undergo encounters with Mars, but can approach the Earth only when the nodal distance gets close to 1 AU.

then is ejected and put by Earth encounters in the 5/2 resonance, which eventually sends it to the Sun.

Other behaviours are possible. As we have already anticipated, four clones over 21 never reach the Earth's orbit. Three of them suffer only numerous but weak close encounters with Mars, with semimajor axes varying only between 2.66 and 2.68 AU and the eccentricity remaining always smaller than 0.6. Clone $2O+$ suffers stronger encounters with Mars: for the first 7 Myr its semimajor axis a is less than 2.7 AU, but then an encounter with Mars moves it beyond the 8/3 resonance, and then a starts drifting between 2.72 and 2.78 AU. But since the eccentricity remains < 0.6 during all the integration time, the orbit stays always in the Mars–crossing region and never reaches the Earth.

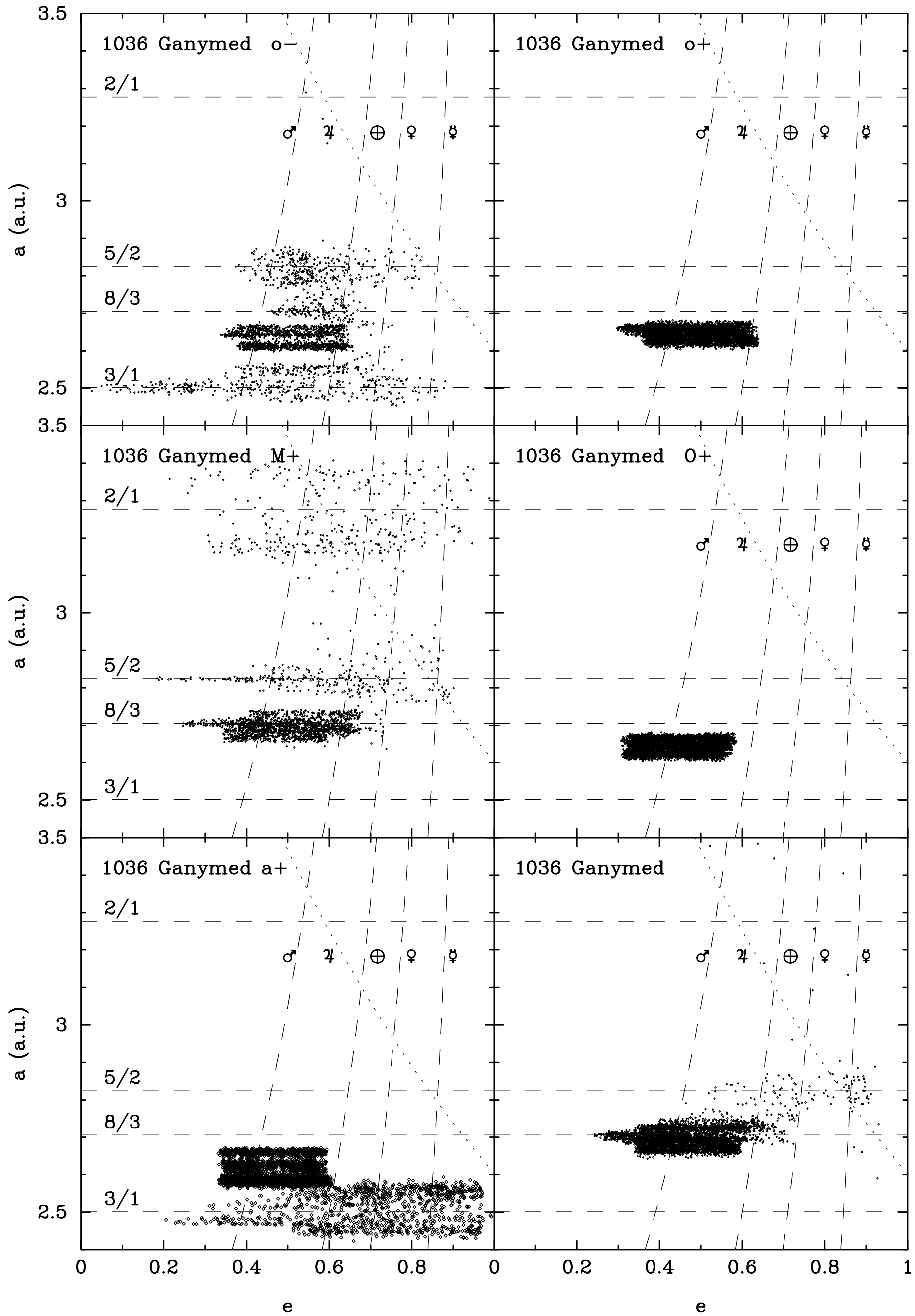

Fig. 5. The evolution of six Ganymed clones in the a vs. e plane. The horizontal dashed lines correspond to the main Jovian resonances. Also shown are the curves corresponding to perihelion distances equal to the semimajor axes of the four terrestrial planets and aphelion distance reaching Jupiter.

3. RMVS3 integrations and statistics

In order to get better statistics we also computed the orbital evolutions of many Ganymed clones using the SWIFT/RMVS3 integrator of Levison & Duncan (1994) and the computer labeled 2. This integrator is based on the symplectic algorithm of Wisdom & Holman (1991), but with substantial modifications in order to deal with planetary close encounters. Actually, it handles close approaches with the planets by performing a kind of time step regularization. More precisely, the chosen initial (and maximum) integration time step is first decreased by a factor 5 whenever the considered orbit gets inside 3 Hill's radii of a planet; for closer encounters, penetrating within the planet's Hill sphere, the time step reduction factor is increased to 10 and the keplerian part of the Hamiltonian assumes that the planet (instead of the Sun) is the primary body.

We performed these integrations using successively 2 initial stepsizes of 15 and 7 days, hereafter denoted respectively by RMVS3(15) and RMVS3(7). The results are summarized in Table 2.

Orbital evolutions as diverse as those described in Sect. 2 are found using the RMVS3 integrator, but the general picture is unchanged. For instance, we have calculated the overall residence times of the clones in different zones of the orbital element space during their evolutions. We have divided the (a, e, i) space into cells of equal size (0.1 AU in a, 0.05 in e and $5°$ in i) and we

have computed the total time spent by our integrated orbits in each cell. In this way, we obtain a density distribution in the (a, e, i) space, whose projections on the (e, a) and (i, a) planes are shown in Figs. 6, 7 and 8, separately for clones integrated by the Bulirsch–Stoer, RMVS3(15) and RMVS3(7) algorithms. In each case, the residence time has been normalized by the number of integrated particles, and therefore shows the amount of time an *average* particle spends in the various regions of the orbital element space. In a steady state scenario, these plots would represent the expected orbital distribution of objects coming from Ganymed–like initial conditions. In other words, the probability of finding an object in a given cell is proportional to the total time spent in that cell by the integrated test particles (strictly speaking, this is true only outside the region of origin).

The three plots look quite similar from a qualitative point of view and confirm the results described in Sect. 2. The distributions all show a concentration at semimajor axes close or inside the strong Jovian mean motion resonances, whereas no time is spent with $a < 2$ AU. However, one can note that the clones integrated with Bulirsch–Stoer and RMVS3(15) spend more time in the Earth–crossing region than those integrated with RMVS3(7). As for the inclination, it remains always high, with large oscillations due to the already discussed Kozai–like mechanism.

The number of bodies which become ECs is practically the same in the three sets of integrations: 17/21 with Bulirsch–Stoer, 15/20 with RMVS3(15) and 16/20 with RMVS3(7). However, we have found that in the Bulirsch–Stoer and RMVS3(15) integrations the majority of the orbits (respectively 13/21 and 14/20) are strongly affected by mean motion resonances with Jupiter, whereas only 9/20 orbits enter into some mean motion resonance in the RMVS3(7) integrations. This fact is consistent with the differences between Figs. 6, 7 and 8, and probably explains why only 6/20 clones hit the Sun within 10 Myr in the RMVS(7) set. However, its reasons are unclear. A possibility is that the efficiency of the Martian encounters in random–walking the orbits is affected by the chosen time step when RMVS3 is used, since as discussed above with this integrator the stepsize reduction is not fully adapted to the specific encounter in progress, but is always a fixed fraction of the initial value — which must be large enough to get a high integration speed. However, this explanation is not really consistent with the findings reported above, which show a closer similarity to the Bulirsch–Stoer results when using the longer time step. Possibly, our sample of clones is still too small to assess from a statistical point of view the reliability of RMVS3 with this kind of orbits. In any case, the differences among the results obtained with the three sets of clones are of minor importance, if we aim at understanding the dynamical mechanisms affecting this kind of orbits and estimating their lifetimes. From this point of view, the main conclusions discussed in Sect. 2 have been fully confirmed.

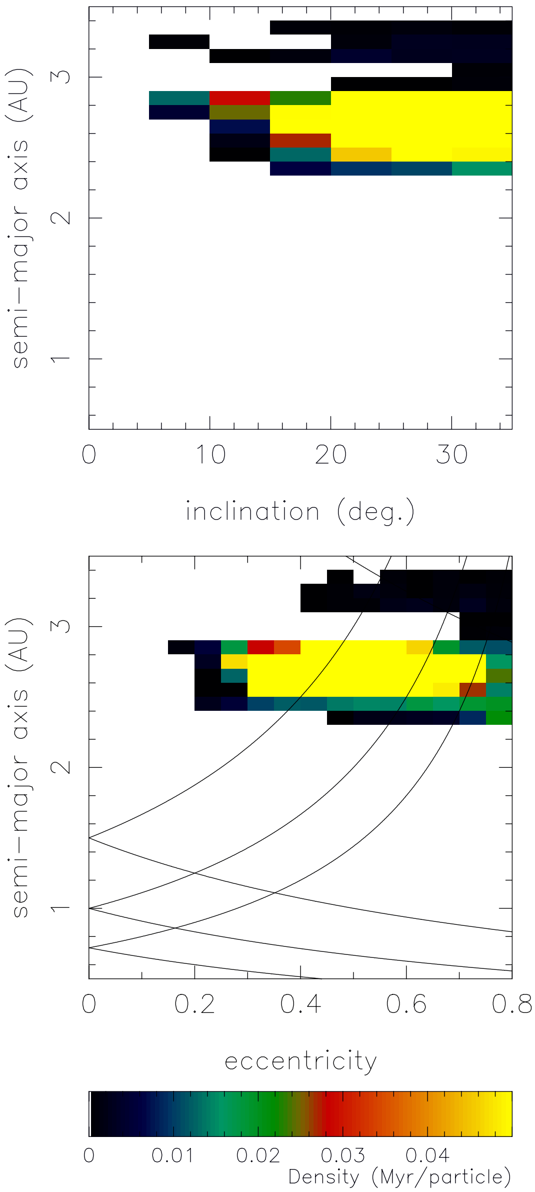

Fig. 6. Mean residence time of the 21 Ganymed clones integrated using the Bulirsch–Stoer algorithm. The grey scale gives the average time (Myr per particle) spent in the different cells, the darkest being the shortest.

4. Implications and open problems

What are the implications of the results reported above for the origin of Ganymed and the other NEAs with similar orbits? The main constraint is provided by the short dynamical lifetime of this kind of orbits, ≈ 10 Myr as we have seen. In order to understand this constraint, we have to analyse the "demography" of these bodies.

There are about 15 objects with diameters $D > 20$ km among the Mars–crossing asteroids, 3 of them (1036 Ganymed, 2204 Lyyli and 132 Aethra) with Ganymed–type orbits (that is, semimajor axes between the 3:1 and 5:2 resonances and proper inclinations $> 20°$, well above the ν_6 secular resonance) and 3 more (475 Occlo, 344 Desiderata and 796 Sarita) with somewhat lower inclinations ($18° < i < 20°$). We have not checked whether the latter 3 bodies are also located above ν_6, but it is interesting to note that one of them, 344 Desiderata, is a fairly big

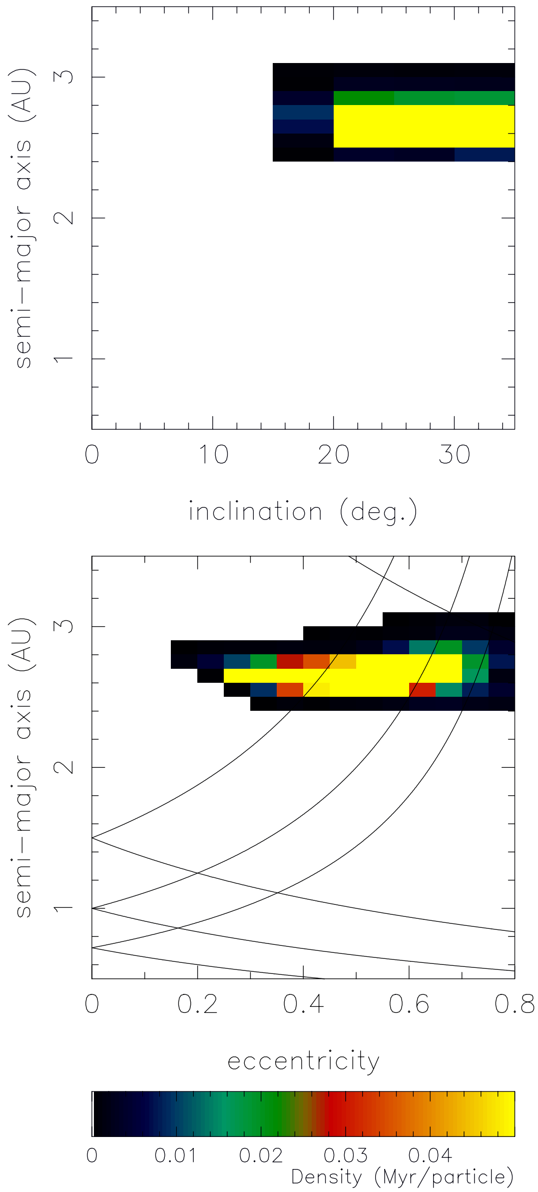

Fig. 7. The same as in Fig. 6, but for the Ganymed clones integrated with RMVS3(15).

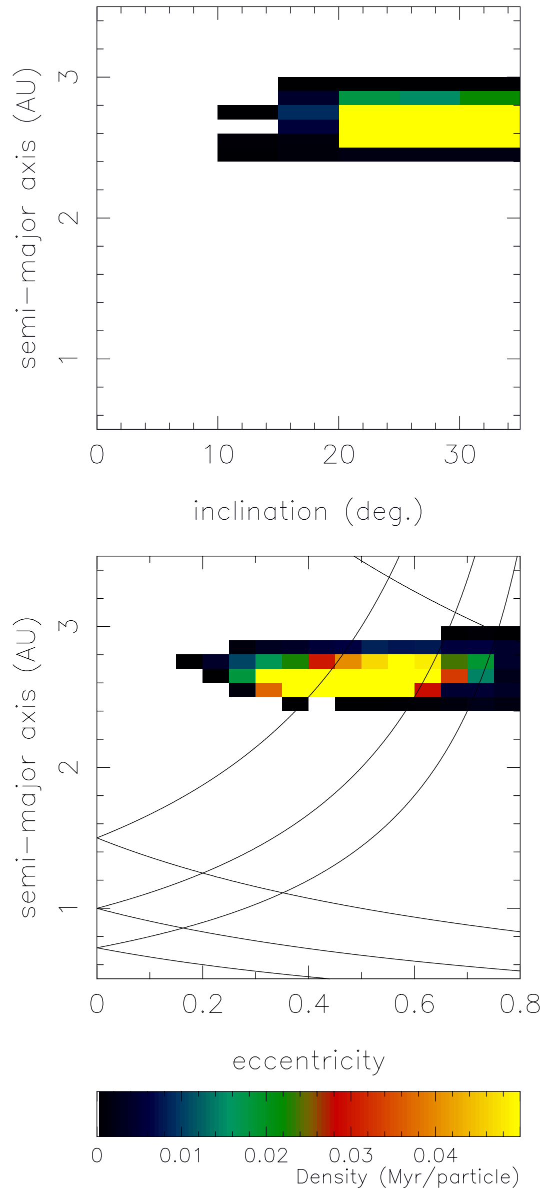

Fig. 8. The same as in Fig. 6, but for the Ganymed clones integrated with RMVS3(7).

asteroid (about 132 km in diameter). We do not know whether these other Mars–crossers have dynamical lifetimes as short as Ganymed [recall that the MB2 objects of Migliorini et al. (1998) had an average lifetime of about 40 Myr] — but if so, where do they come from?

The simplest solution would be that, like the other types of Mars–crossers, these bodies would be supplied by chaotic diffusion from the main–belt population having similar values of a and i, but lower eccentricities (Migliorini et al. 1998; Morbidelli & Nesvorný 1999; Michel et al. 1999). However, according to the catalogue of asteroid orbits maintained by E. Bowell (http://www.lowell.edu/pub/elgb/astorb.html), which is almost complete for bodies of diameter > 20 km (V. Zappalà, private communication), there are only 16 such objects in the putative source population, with main–belt orbits above ν_6 and with semimajor axes between 2.5 and 2.8 AU. This is certainly not enough to sustain a loss of $0.5 \times 3/10 = 0.15$ Ganymed–like objects per Myr over the age of the Solar System. Here we have assumed that 3 of the Mars–crossers with Ganymed–like orbits have lifetimes of about 10 Myr: but the basic conclusion would not change much if we had counted only Ganymed, or we had included all the 6 MB2s larger than 20 km and assumed the Migliorini et al. average lifetime of 40 Myr.

Of course there are other conceivable sources for the Ganymed–like (MB2) Mars–crossers, e.g. (i) main–belt asteroids with lower inclinations, and "jumping" through ν_6; (ii) Phocaea–group bodies, which are located above ν_6 but would have to jump outward through the 3:1 resonance; and (iii) Jupiter–family comets, which may become dynamically decoupled from Jupiter (such as P/Encke, see Valsecchi et al. 1995).

However, none of these sources is very attractive, because neither chaotic dynamics nor velocity increments associated to collisions appear likely to provide efficient transfer routes to the MB2 region.

Consider for instance the Maria family, whose largest members have sizes close to that of Ganymed and bear a spectral resemblance to it (Zappalà et al. 1997). This family is located near the outer edge of the 3:1 resonance at relatively high proper inclinations ($\approx 15°$), which however are much lower than that of Ganymed and such that the entire family lies below ν_6. Plausible ejection velocities following the family formation event (a few hundreds m/s) are not enough to raise the inclination beyond ν_6, into the MB2 zone. On the other hand, in none of our integrations we have observed the inclination of Ganymed to change by such an amount, unless the body had fell into a strong resonance; but in that case, typically it would survive for only a few Myr, and would not be likely to come back to the initial state. Even if the resonant locking were temporary, as for clones $2a+$ and $2a-$ discussed in Sect. 2, it would be necessary to assume that the 3:1 resonance had pumped up not only the eccentricty but the inclination too (by some $10°$) during the locking interval, and then the body had been extracted out of the resonance (plausibly, by an Earth encounter) and eventually had its eccentricity decreased again to put it into the MB2 region. Clearly, such a scenario cannot be excluded *a priori*, but does not look likely.

An alternative possibility may be that Ganymed is a former member of a long-lived tail of a primordial main–belt population above ν_6, now almost depleted. Were Ganymed a single, peculiar object, this would be plausible; but if 2204 Lyyli and 132 Aethra have also lifetimes as short as 10 (or even 40) Myr, this explanation becomes very unlikely. In summary, we conclude that the origin of Ganymed and its siblings is still an open problem, with no straightforward solution at hand.

Our results have also some implications on the possible connection of Ganymed with the meteorites. Zappalà et al. (1997) have stressed the similarity of Ganymed's visible reflectance spectrum with those of the main–belt asteroids classified by Gaffey et al. (1993) in the S(IV) spectral subclass, the only one within the S taxonomic class which is probably related to the ordinary chondrites (Chapman 1996). If this is the case and Ganymed's composition is chondritic, its current orbit probably implies that ordinary chondritic material exists also out of the so–called inner asteroid belt (inside the 3:1 resonance). On the other hand, the meteorite Earth–delivery efficiency of bodies with this type of orbits is certainly low, because in most cases they are short–lived when they become Earth–crossing. As shown by Morbidelli & Gladman (1998), only about 0.1% of the particles inserted into the 3:1 resonance eventually collide with the Earth; for the MB2 asteroids, the overall percentage is probably smaller, as many of them eventually fall into the even more inefficient 8:3 and 5:2 resonances. Also, the population in this region and the neighbouring lower–inclination part of the main belt is quite sparse, and cannot supply a large flux of small fragments. Therefore we conclude that this region of the asteroid belt is not likely to provide many meteorites.

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